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EFFECT OF ELIMINATION OF NITROGEN AND/OR HYPOXIA OR RESTRICTED VISUAL ENVIRONMENT ON COLOR VISION AND RANGE OF ACCOMMODATION

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Myron L. Wolbarsht

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Myron L. Wolbarsht

Charles W. White

W. Banks Anderson, Jr.

Departments of Ophthalmology and Psychology

Duke University

Durham, N. C. 27706

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Abstract

The effects upon range of accommodation and color vision of reduced atmospheric pressure, at partial and complete elimination of nitrogen, of hypoxia, and of exposure for varying periods of time to restricted visual environment, have been studied alone or in various combinations. Measurements were made on the electroretinogram, the electrooculogram, and the diameter of the retinal vessels as an indicator of blood flow to the retina at the time of total elimination of nitrogen. An objective method was used to test range of accommodation. In the color vision test the flicker colors of a Benham's top were matched with a colorimeter.

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The cosmonauts engaged in moderately long space flights have reported changes in their color vision and their range of accommodation.

The apparent difficulties with color vision were reported as confusing red with yellow panel lights after several days in space flight. A brightness matching test was arranged for subsequent flights which consisted of several color panels and a set of chromatically neutral panels that made up a gray scale. At various times during the space flights the astronauts selected a gray panel to match the brightness of each of the colored panels. Several changes in the luminance matching combination of gray and color panels occurred during the experiments. The biggest change was an apparent increase in the brightness of the blue panel, i.e., during the course of the experiment, the panels selected to match the blue changed from darker grays to lighter grays. The relation between this outcome and the previously reported yellow-red discrimination difficulty is problematical.

Several factors could have contributed to these apparent effects as there were several changes in the environment present at the same time. Also the data indicating the changes in color vision and range of accommodation are rather meager. It is difficult to ascertain if these are true effects or if true, which of the changes in the environment are responsible.

The decrease in the range of accommodation may be due to the restriction in visual environment, that is, a lack of features over the middle and far ranges outside of the space craft. This could lead to continual accommodation on near objects with possible fatigue of the

ciliary muscle. A second possibility is that low G forces which produce a general lessening of postural muscle tone might produce a similar lack of tone in the ciliary muscles. Also, the absence of gravity would change some of the tension required by muscles to suspend the lens. All these might result in weakening of the ciliary muscle. Slight hypoxia of the central nervous system could also cause a lessened range of accommodation by blurring the target or weakening the accommodative effect. The hypoxia could be due to possible shallow breathing.

Also considering the age of the cosmonauts, it is not surprising that some of them would complain of apparent difficulty in seeing near objects as anything leading to fatigue in the ciliary muscle would produce changes in focal ability in the range used by the crewmen, especially if they were slightly hyperopic.

In a long series of experiments Carapancea and his associates (1969, 1970, 1971, 1972) indicated that range of accommodation was affected adversely by a combination of altitude and lowered oxygen tension. The experiments were on both rabbits and a selected population of aviators. Carapancea believed that the decrease in the range of accommodation was caused by fatigue in the ciliary muscle. This fatigue resulted from a hyperopia a induced by an increased intraocular pressure (relative to the outside of the eye) from the altitude. This effect appeared to be aggravated for any subjects who were hyperopic originally. In the case of the rabbits, at least, rather extreme altitudes were used and the animals were generally unconscious after a brief exposure.

Simple hypoxia has already been shown to have an effect on visual performance, especially color vision (Kulbrick, 1970). It is also possible that changes in the retinal circulation could affect color vision. The retinal circulation appears quite sensitive to manipulations of the gaseous environment of the body. Exposure to 100% oxygen at normal (sea-level) atmospheric pressure has for example been observed to produce marked vasoconstriction of the retinal vessels (Cusick, et al, 1940). These changes become even more pronounced when the environmental pressure is increased (Frayser and Hickam, 1964; Frayser, et al., 1967; Dollery et al., 1964; Anderson, 1968). In dogs, exudative retinal detachments (Beehler and Roberts, 1968) and nerve fiber layer infarcts (Margolis et al., 1965) (cotton wool exudates) have been observed following hyperoxygenation, leading some authors to speculate that ocular toxicity might be the limiting factor in hyperoxic exposures (Margolis and Brown, 1966).

When the environmental situation is reversed and air is inspired at altitude, pronounced retinal vascular changes are again observed (Frayser et al., 1970; Singh et al., 1969). Vascular dilatation, increased tortuosity of vessels, papilledema and preretinal hemorrhages have been observed. In one case, the hemorrhage occurred at the macula and was therefore symptomatic (Frayser et al., 1970).

The subjects in the present series of experiments were exposed both to altitude and pure oxygen. It seemed appropriate therefore to look for possible changes in retinal vascular caliber and flow dynamics. Although changes in carbon dioxide tension have upon occasion been

evoked to explain changes in retinal vascular caliber (Singh *et al.*, 1969; Lambertsen, 1965), most workers agree that changes in oxygen tension are by far the major determinant of retinal vascular caliber and circulation time (Cusick *et al.*, 1940; Frayser and Hickam, 1964; Dollery *et al.*, 1964; Frayser *et al.*, 1967; Anderson, 1968; Frayser *et al.*, 1970; Spalter *et al.*, 1965; Anderson *et al.*, 1967). Nitrogen has never been shown to affect retinal vessels at normal, elevated, or reduced atmospheric pressures. If retinal pO_2 is the major determinant of retinal vascular caliber and flow, the combination of oxygen breathing and altitude should result in a normal retinal picture provided the arterial pO_2 approximated that breathing air at sea level.

Kitayev-Smyk (1969) reported that there was some disturbance to color vision during short periods of weightlessness. Contrast sensitivity to red and yellow increased during weightlessness while that to blue decreased. However, the weightlessness test conditions are probably not equivalent to those in a space craft. These tests were only 25-30 seconds long and were preceeded or followed by high G-forces as they were produced by the parabolic trajectory of an aircraft.

Perhaps more to the point, after we analyze all the data on the cosmonauts, is a paper by Zoz (1969). This paper concerns people working in restricted visual environments. Zoz indicated that workers who used microscopes or other optical instruments during a large part of their tasks had some constant disturbances in the stability of their color discrimination. This change arose if the work involved prolonged visual strain. This situation may be comparable to that of

a space flight in that only near objects are presented (the immediate environment of the space craft). If this task produced any considerable amount of visual strain, color vision could be affected.

The narcotic effects of high pressure nitrogen have been known for many years. Reviews of the subject, in addition to descriptions of new work, have been given by Bennett et al. (1960, 1964, 1969). The narcotic effect of the high pressure nitrogen is shared by the other so-called "inert" gases. If we accept the narcotic effect of nitrogen at high pressures, it is reasonable to extrapolate these effects back to normal atmospheric levels. From this extrapolation we could infer that the normal effect of nitrogen in the atmosphere is to slightly inhibit the nervous system. This inhibition, of course, would be normal, i.e., the way that the nervous system works all the time. If nitrogen were then to be removed as, for example, in 100% oxygen at 167mm pressure, the nervous system would be free of any depressive or inhibitory effects of nitrogen resulting in a hyperexcitable state. Obviously the effect is not a large one, as many people have breathed 100% oxygen at 30,000 feet for long periods of time without noticing any gross functional changes in the nervous system.

The present series of experiments were designed to test the possibility of subtle effects of nitrogen upon the nervous system. This was done by progressively removing nitrogen from the atmosphere. Then tests of high sensitivity were used to show any subtle change in either color vision or range of accommodation. These two functions were selected because

they were judged to be ones involving maximum integrative and detailed balancing of a large part of the nervous system. These are not simple reflex reactions, but ones that depend upon judgements.

The vast majority of tests for range of accommodation have one thing in common, the end point is the same. That is, the subject reports his inability to focus upon the target at the end of the range. This test depends on image quality and thus is subjective. The subject must decide when the image of the target is not "sharp". Various targets and various ways for manipulating them to bring them closer to the subject have all been used. Fitch (1971) has discussed how results are effected by varying the presentation of targets. In his data the largest ranges of accommodation are measured binocularly, with the subject controlling the movement of the target directly. The smallest ranges were measured monocularly, with the target movement not under the control of the subject. Each method had an internal consistency indicating that any method could be used for valid results. Also, differences between the various methods were small, although quite consistent.

As mentioned above previous exposures to 100% oxygen have not been accompanied by gross changes in either color vision or range of accommodation. Therefore the effect to be tested is a subtle one. In order to test this subtle effect, the following criterion was used: the measurement must have a sharp end point, i.e. two targets must be matched or an objective report made which must require no judgement. Tests for both color vision and range of accommodation were devised which met this criterion.

The test for range of accommodation embodied refraction with the use of the laser speckle pattern. In essence the subject merely reported the direction of movement of grains in a laser pattern. Motion in one direction indicated hyperopia (focus behind the retina); motion in the opposite direction indicated myopia (focus in front of the retina). Concave lenses were presented to the subjects in increasing strengths until the motion of the grains began again. Occasionally there was uncertainty when this point was reached. However, the adding or subtracting of an additional eighth diopter was sufficient to start the grains moving again. Thus it was quite easy to show the near point of the subject's range of accommodation. This test can be thought of as a form of self-retinoscopy.

For color vision, the rationale was somewhat different. The best possible test of color vision should produce the same color in two ways using slightly different visual pathways. Then the function of each should be tested in the same way. Although we could expect that the changes in the nervous system due to the different environmental conditions would change both systems, it is unlikely that we could change both in a compensatory fashion. Thus, to match colors produced by two systems would be a subtle test of the correct function of both. Flicker colors certainly could not stimulate receptors in the same way as pure spectral colors. The appearance of a flicker color would come from the interpretation of the neural code by higher visual centers in a somewhat different fashion than the same apparent color produced by pure spectral stimulation. Our test was designed to produce flicker colors that could be matched by

spectral colors in an anomaloscope. Flicker colors form the basis of the so-called Benham's top illusion, in which a disc with a variety of patterns, usually of short lines, is moved at reasonably high speeds on a turntable. Bands of different colors are produced depending on the speed and the pattern.

Although there is no completely satisfying explanation of the visual mechanism responsible for producing the flicker colors, that offered by Pieron (1952) comes as close as any. In addition it offers a good statement of the phenomenon itself. Pirenne and Abbot (Pieron, 1952) offer a convenient translation which is quoted in the following paragraph:

> "The explanation of these colorations is found in the differences between the time-constants of the establishment of sensation for the fundamental systems (Pieron, 1923). The blue system is the slowest to appear and to reach its transitory maximum, the slowest also to disappear; the red system is the quickest of the three. When a pencil of white light is suddenly made to act, there is an initial unbalance which favours the red excitation, and when the light ceases to act the last phase in the persistence of the image favours blue. This phenomenon is, however, too brief for it to be seen normally. The rotating disc of Benham's Top, where a white half-circle succeeds a black, effects brief stimulations by white light. Black circular stripes disposed on the white sector shield corresponding retinal areas from direct luminous stimulation. But at this level a diffusion of the excitation from the surrounding areas must be produced, extending to the whole of the stripe if this be thin enough; this diffusion will act selectively on the chromatic systems. In the initial phase, when the unbalance is in favour of the red component, the diffusion of the excitation will lead to the production of a reddish coloration of the dark rings resulting from the short annular stripes. In the second phase, the green coloration diffuses, the unbalance favouring mostly the

> second component. In the last phase, it is the blue coloration which, due to its slow growth, reaches its maximum while the others have already noticeably declined. The coloration obtained, red, orange, yellow, green, green-blue or blue depends upon the position of the stripes on the white sector of the disk and upon the speed of rotation, that is to say, on the exact value of the time delay."

METHODS

All experimental studies were conducted in the series of chambers in the F. G. Hall Laboratory at Duke University Medical Center. The chamber and air lock are capable of going from 1 torr to approxi-mately 31.3 atmospheres. The chamber gas was pure nitrogen in order to reduce fire hazard, except for the sea level run and the 79% oxygen 21% nitrogen at a reduced pressure (9500 feet). All electrical equipment had a separate nitrogen purge line in order that no expired gas mixtures containing oxygen could come in contact with possible sparks. The subjects wore head tents (or hoods which completely surrounded the head). These were taped to the chest. This arrangement was a slightly modified version of the one described by Saltzman et al. 1971. A schematic of the gas flow connections to the head tent is shown in Figure 1. The head tents were provided with a small cappable tube through which the subject could drink by means of a straw. Milk shakes and noncarbonated drinks were given at regular intervals to ensure the comfort of the subjects.

A plate glass window was inserted into the front of the head tent in order to allow non-distorted vision. Although the tent was kept

inflated, the window could be moved by the subject as to allow him to adjust his eye position properly to the various optical equipment used. The gas mixtures within the head tents were sampled and analyzed continually for oxygen content. The chamber pressure was modified slightly to maintain the oxygen tension at the desired level (that present in a sea level atmosphere). No discomfort was experienced by the subjects wearing the head tents. Positive pressure was maintained inside the head tent at all times with large flow rate to prevent build up of CO_2. Waste gases from the head tents were vented into the chamber. The chamber atmosphere was changed continuously to prevent build up of O_2 and CO_2. The temperature and humidity within the chamber were controlled to be well within the comfort range for all subjects. In those runs in which color vision and accommodation were tested, the subjects moved in a regular sequence around the chamber to be tested.

Subjects

Five subjects participated in the color vision and range of accommodation experiments. All of these subjects had 20/20 or better acuity. Three subjects wore corrective lenses through the experiment. In addition to selected members of these five subjects, two additional subjects were used in various other tests.

The color vision of every subject was classified normal according to the H-R-R Pseudoisochomatic Plates (American Optical Company, 1956). None of the subjects made errors on that screening test. Color

discrimination ability was tested by the Farnsworth-Munsell 100-Hue Test (Farnsworth, 1957). One subject was rated "superior" and four were classified "average" according to the 100-Hue Test manual. The results in percentiles from the 100-Hue test norms for unselected subjects between ages 15 and 45 are summarized in Table 1, along with other descriptive characteristics.

Range of Accommodation Test

As described in the introduction the range of accommodation test was an objective measure of the refraction of the eye based upon the appearance of a laser sparkle pattern reflected from the matte surface of a slowly moving drum. A Green's phoropter was used to force the subject to accommodate. The target (shown in Figure 2) was a cross made of three fine horizontal and three fine vertical lines with the laser spot located just off the fixation point. The subject was instructed to focus on the cross and keep it as clear as possible. At the same time he observed the speckle pattern of the laser, which was slightly eccentrically to his point of fixation. His report on its motion established the focal status of his eye with respect to the cross. If the subject had difficulty in determining the direction of motion, i.e., if the direction of motion were random or stopped occasionally, the pattern was judged within the range of accommodation. The matching background surface was illuminated with approximately 10 foot lamberts of white light. The laser was outside the chamber and its beam was projected inside

through a porthole. The beam was not expanded and was about 3 mm in diameter as terminated on the drum. The phoropter was located approximately 1 meter from the drum. The lenses in the phoropter were controlled by the observer. All subjects were right handed and used their right eye in the phoropter. No attempt was made to compensate for changes in astigmatism as a function of change in accommodation. The entire process for each subject took three minutes or less. All subjects were tested immediately before the altitude runs and again immediately prior to the descent. This ensured a maximum time exposure to the altitude before the final test. The range of accommodation of each subject was also tested by conventional means outside of the chamber. A Snellen chart at 20 feet was the far point target. For the near point a target similar to that in Figure 2 was used.

Color Vision Test Apparatus

The flicker-color matching apparatus was designed to produce a rectangular field containing the flicker-color (or Benham top) stimuli and an adjacent matching field which was variable in chromaticity and luminance. It is a modification of an anomaloscope described by Festinger et al (1971). The two fields as they appeared to the subject are depicted approximately to scale in Figure 3. Subjects viewed the stimuli monocularly through a circular plate-glass window 40 mm in diameter, with his right eye as close to the window as possible. The viewing distance to the colorimeter field was 36 cm.

The matching field was produced by a filter colorimeter suggested by Burnham (1952). Light from a 6 volt, 9 amp, ribbon filament lamp was collimated by an achromatic lens and projected onto an opal glass surface through a filter slide, as shown in Figure 4. The filter slide was a square, 80 x 80 mm, made up of three filters mounted between cover glass. The upper half of the square was green (Wratten No. 74), one of the lower quadrants was red (Wratten No. 29) and the other quadrant was blue (Wratten No. 47). The filter slide was mounted on the pen holder of an X-Y graphic plotter. Plotting movements of the pen holder carried the filters accurately and reproducibly to any position within the light beam. The opal glass was cemented to an integrating bar made of Plexiglas 36 x 36 x 90 mm, with the long sides polished. The filtered light, after diffusion by the opal glass and internal reflection within the integrating bar, produced a uniformly mixed colored field on a second opal glass surface at the front end of the bar. The subject controlled the chromaticity of this matching field by varying the position of the filter slide. This X-Y motion determined the relative contribution of each filter to the mixture. The subject controlled the horizontal and vertical position of the filter slide by turning two ten-turn potentiometers on battery sources that were connected to the X-Y plotter. The control knobs were unmarked. The use of the X-Y plotter to move the filters instead of the microscope stage as used by Burnham (1952) enabled remote control and accurate read-out of the slide position. The position of the filter slide was indicated by two digital volt meters connected to the horizontal and

vertical inputs of the plotter.

The luminance of the matching field could be varied by insertion of neutral density filters of either 0.3 or 0.6 density values (Wratten No. 96) in front of the colorimeter field.

In analyzing the results of the colorimeter settings, the horizontal and vertical positions of the filter slide were converted to three numbers representing the relative contribution of each filter to the mixture in the matching field. The chromaticity coordinates of the mixture were then computed from these three proportions, the tristimulus values of the source, and the filters. Any additional neutral filters were included in the luminance computation.

The other part of the stimulus field contained the flicker-color. This was produced by rotating a cylinder with the pattern illustrated in Figure 5 wrapped around it. This pattern is the familiar Benham disc pattern translated into a cylindrical form. The pattern was constructed from white bond paper, opaque black paper, and India ink line segments. It was illuminated from within the cylinder by a lamp (General Electric #1493) and was spun at seven rotations per second. That rotation rate produced optimum flicker colors for three observers in a previous pilot experiment. The direction of rotation was such that the leftmost bands in Figure 1 were produced by the line segments immediately following the black half of the cylinder, and the rightmost bands were produced by the segments immediately preceding the black sector. The luminance of the white portion of the pattern was measured with a Macbeth photometer at 3.2 foot Lamberts (Ft. L).

Color Vision Procedures

The task of the subject on each trial was to adjust the colorimeter to match as closely as possible four targets in the flicker-color field. The four targets were the three sets of bands in Figure 1, identified as left, center, or right, and the background area between the sets of bands. Since the maximum luminance of the colorimeter was less than the background luminances, a 1.0 neutral density filter (Wratten No. 96) was swung into position between the rotating cylinder and the mirror while the subject matched the background. The subject always matched the targets in blocks of 16 trials with four matches of each target in a randomly permuted sequence. Each block required 15 to 20 minutes to complete. All subjects were given three or more practice blocks before beginning the experiment. The data reported here are two blocks of 16 matches per subject in each condition. These matches were made during the last two hours of each session, except for one block per subject in the 100% oxygen run which was run during the first half of that session.

Retinal Circulation

A Zeiss fundus camera was used to photograph the ocular fundus. During the chamber run a series of photographs were taken at various times to indicate retinal vessel caliber. For maximum contrast between the retinal vessel and the retina, a filter was used to give red-free illumination. Measurements were made of the vessel caliber directly from the negatives to minimize changes in size through the printing process.

At sea level, the partial pressure of O_2 in dry atmosphereic air is 159 mm Hg (20.93% of 760 mm Hg). At 20,000 feet it is 73.7 mm Hg but if O_2 is the only inspired gas it exerts the full barometric pressure which is 352 mm Hg. The actual inspired pO_2 before the photographs were taken would be lowered by leaks around the mask. Leaks were probably minimal with the scuba mouthpiece and nose clip apparatus which was used during the photographs. Assuming an alveolar pCO_2 of 40 mm Hg and a pH_2O of 47 mm Hg, an alveolar pO_2 of 265 mm Hg would result. The arterial pO_2 would be a few millimeters of Hg lower. This arterial pO_2 is still higher than that measured breathing air at sea level (100 mm Hg), but not as high as that obtained breathing pure oxygen at sea level (670 mm Hg). The small increment in arterial pO_2 with oxygen breathing at altitude was not associated with any significant difference in vascular diameter as compared with the air breathing at normal pressure controls. The findings from this series of experiments therefore tend to confirm the hypothesis that pO_2 is the major determinant of retinal vessel diameters.

The fluorescein angiograms revealed no abnormalities. Specifically there was no unusal staining of the optic discs (as may occur in papilledema), no evidence of vascular spasm (focal or otherwise) and no evidence of abnormal vascular filling time.

Homologous retinal vessels in each subject were identified from prints made of each negative. Blurred exposures were not used. Retinal vessel diameters were measured from the negative by microscope using a

graduated reticle in the ocular.

At least three arterioles and three venules were measured for each subject under the two conditions of the experiment. Measurements were made to the nearest half scale reading. To minimize measurement bias, all measurements were made upon one negative before moving to the next and homologous vessels were not measured sequentially. Measurement sites were identified from the positive prints and the measurer was "blind" to the values obtained. Figure 6 shows a typical print with the measurement sites indicated.

A rapid injection of approximately 5 ml of a 10% fluorescein solution displayed the retinal circulation. Single photographs were taken at various intervals following the injection, until approximately 20 minutes post injection.

Dark Adaptation

The dark adaptations were done on a standard Goldmann/Weekers adaptometer (Haag-Streit). The subject was light adapted for two minutes at 300 millilamberts luminance, and then determinations of threshold were made at approximately two per minute for the next 20 minutes.

Electrooculogram (EOG)

In this test the corneo-fundal potential is measured by placing electrodes on the skin medial and lateral to the globe. The method used is a modification of that introduced by Arden *et al*. (1962). With the electrodes in place the subject makes voluntary horizontal eye

movement between two fixation points, usually at about one or two per second. Regular movements are easily made. During the test, a series of these movements are made for a period of about ten seconds, approximately one period per minute during the time of dark adaptation. The maximum change in ratio of amplitude from the light adapted to the dark adapted state is the measure used. A ratio of about 2:1 is generally considered to be normal. Changes from this are characteristic of certain types of retinal disorders. Conventional electronics were used throughout: Tektronix 122 preamplifiers and a Grass dynagraph ink recorder.

Electroretinogram (ERG)

The ERG was recorded in conventional fashion with a Burian-Allen contact lens electrode. The electrodes were connected to a Grass amplifying system (dynagraph) and displayed on a Tektronix Type 564 storage oscilloscope.

The stimulus was provided by Grass Model P-2 photostimulator, approximately two feet from the subject's eye. The photostimulator was mounted outside of the chamber. The light entered through a porthole and was reflected into the subject's eye from a large mirror.

The subject was placed in total darkness for approximately 20 minutes, at which time the dark adapted ERG was measured. The subject was then light adapted for approximately five minutes with 100 millilamberts luminance. Immediately following this the light adapted ERGs were recorded to a short series of single light pulses.

Protocol for Experiments

In all experiments, except as specifically described otherwise, the subjects wore head tents, and there were two testing runs at each altitude with test for color vision and range of accommodation tested in each.

Schedule 1--Altitude equivalent 7,250 feet (P_B+47=447 mmHg) 70% nitrogen, 30% oxygen, where oxygen is maintained at the same absolute pressure as at sea level.

The pressure in the chamber was reduced over a period of nearly an hour to altitude. During this time the subject was kept busy doing various close work tasks. This altitude level was maintained for a period of six hours, at which time descent was started. Repressurization was accomplished over a period of 30 minutes.

The following tests were taken while the subject was at altitude: range of accommodation; the sensitivity and integrity of color vision as tested by a variation of Benham's top illusion by matching the flicker colors in an anomaloscope. Electroretinograms, electrooculograms, and a dark adaptation test were also taken unilaterally during one run.

Schedule 2--Altitude equivalent to 14,000 feet (P_B+47=447 mmHg) 60% nitrogen, 40% oxygen, with the oxygen maintained at the same absolute pressure as at sea level.

The pressure in the chamber was reduced over a period of nearly an

hour to altitude. During this time the subject was kept busy doing various close work tasks. This altitude level was maintained for a period of six hours, at which time descent was started. Repressurization was accomplished over a period of 30 minutes.

The following tests were taken while the subject was at altitude: range of accommodation; the sensitivity and integrity of color vision as tested by a variation of Benham's top illusion by matching the flicker colors in an anomaloscope. Electroretinograms, electrooculograms, and a dark adaptation test were also taken unilaterally during one run.

Schedule 3--Altitude equivalent to 31,500 feet (P_B+47=207 mmHg) 100% oxygen at the same absolute pressure as at sea level. At this point the subject was breathing 100% oxygen at 31,500 feet.

The pressure in the chamber was reduced over a period of nearly an hour to altitude. During this time the subject was kept busy doing various close work tasks. This altitude level was maintained for a period of six hours, at which time descent was started. Repressurization was accomplished over a period of 30 minutes.

The following tests were taken while the subject was at altitude: range of accommodation; sensitivity and integrity of color vision as tested by a variation of Benham's top illusion by matching the flicker colors in an anomaloscope. Electroretinograms, electrooculograms, and a dark adaptation test were also taken unilaterally during one run.

Only one set of experiments was done at this altitude.

Retinal photographs were taken through the dilated pupil prior to descent to document any changes in the size of the retinal vessels. Also, in some of the subjects arterial pO_2, pCO_2, and pH were measured using an indwelling brachial arterial cannula. Estimation of retinal circulation times and estimates of retinal perfusion were obtained in certain subjects by the injection of 10 mm of 5% sodium fluorescein solution.

Schedule 4--Altitude equivalent to 9,500 feet (P_B+47=533 mmHg). The subject breathed a 79% N_2, 21% O_2 gas mixture at the same pressure as in the chamber. In one of the sets of tests no head tents were worn.

The pressure in the chamber was reduced over a period of nearly an hour to altitude. During this time the subject was kept busy doing various close work tasks. This altitude level was maintained for a period of six hours, at which time descent was started. Repressurization was accomplished over a period of 30 minutes.

The following tests were taken while the subject was at altitude: range of accommodation; sensitivity and integrity of color vision as tested by a variation of Benham's top illusion by matching the flicker colors in an anomaloscope. Electroretinograms, electrooculograms, and a dark adaptation test were also taken unilaterally during one run.

Schedule 5--Altitude equivalent to sea level or 760 mm Hg.

The pressure in the chamber was reduced over a period of nearly an hour to altitude. During this time the subject was kept busy doing

various close work tasks. This altitude level was maintained for a period of six hours, at which time descent was started. Repressurization was accomplished over a period of 30 minutes.

The following tests were taken while the subject was at altitude: range of accommodation; sensitivity and integrity of color vision as tested by a variation of Benham's top illusion by matching the flicker colors in an anomaloscope. Electroretinograms, electrooculograms, and a dark adaptation test were also taken unilaterally during one run.

RESULTS

Retinal Circulation

The results of the vessel width measurements are summarized in Table II. There is little or no difference between vessels measured at sea level and at 100% oxygen at altitude greater than 30,000 feet. This indicates that the retinal vasculature is essentially the same under the two conditions. Thus the degree of oxygenation of the retina would be completely comparable, and any function dependent on oxygen consumption would be unchanged.

Range of Accommodation Measurements

Although many of the subjects showed changes in the range of accommodation, there was no consistent variation. The results are summarized in Table III. The individual results for each subject are shown in Table IV. Some of the subjects showed slight decreases in

range of accommodation in Runs #5 and 6 (hypoxic: simulated 9500 feet with reduced oxygen tension) but this decrease was not constant. A wide variation in subject 4 may have been in a change in criteria, i.e. requiring the speckle stopping more often. A greater sensitivity to the slight hypoxia may be the explanation because of inability to concentrate sufficiently on the fine details of the target in order to make the proper accommodative effort.

Dark Adaptation

The results of the dark adaptation tests showed no significant differences between the experimental tests and the controls. A typical set of curves is shown in Figure 7.

Color Matching

The 1931 CIE x,y chromaticity coordinates and luminance values were computed for each of the 800 color matches (5 subjects x 5 conditions each to 4 targets and 8 matches of these). The group results, averaged across all five subjects are presented in Figure 8. The mean matches for the left and center band and the background appear to change very little among the 5 experimental conditions. The matches for the rightmost bands scatter more on this diagram, probably indicating more variability in the matches for the right bars. More variability was expected for the left and right bars than for the center bars and the background, since the left and right bars appear much darker. The right bars might have been even more difficult to match consistently

due to their greater displacement from the matching field.

The mean results were converted to u,v values in the 1960 CIE uniform chromaticity space system (Wyszecki and Stilesk 1967), as shown in Figure 9. On this u,v diagram equal chromatic differences are more nearly represented by equal distances than on the x,y diagram (Fig. 8). The only obvious change is an increased displacement for the Condition 1 matches of the left bars.

The variability of the individual subjects may be judged from Table V in which all the data for one subject is given.

Subjective reports of the appearance of the flicker colors generally supported the colorimeter matching results, i.e., there were no obvious differences between the experimental conditions. There was one important exception, however. After the two sessions in which sea level air mixture was used at a simulated altitude of 9500 feet, several subjects mentioned that the rotating cylinder appeared different somehow. They described the bands on the cylinder as appearing darker and perhaps more saturated than before. Since this experiment was designed to produce slight hypoxia, the phenomenal dimming was not unexpected. Neither phenomenal effect was reflected in the colorimeter matches, of course, since the colorimeter field's appearance apparently was affected in a similar fashion. Also, there was no evidence that the phenomenal effects differed for the different bands on the cylinder, as would be the case if the relative brightness of different hues were to change.

The mean matching luminances for all subjects depicted in Figure 10 indicated that the three sets of bands differed in brightness as well

as in hue and saturation. The differences between experimental conditions, however, were small and inconsistent among different subjects. The mean luminance across all subjects were 1.1 fL for the left bars, 4.3 fL for the center bars, 1.4 fL for the right bars, and 1.8 fL for the background with the 1.0 neutral density filter. These brightness differences, like the flicker colors, must be due to spatial-temporal interactions produced by the rotating cylinder, since the total flux in each set of bands was the same.

The luminance results confirm a previous report by Festinger, Allyn, and White (1971). They are probably best interpreted in terms of transient masking of the bands by the onset and offset of the background, since similar effects occur in many metacontrast paradigms.

Electroretinogram and Electrooculogram

Both of these tests were normal in all situations. Figure 11 shows a series of ERGs done in light and dark adapted states when the subject was breathing 100% oxygen at 31,500 feet.

DISCUSSION

Range of Accommodation

No consistent change in range of accommodation was seen among the various environmental conditions, indicating that range of accommodation remains essentially constant under the conditions tested. One possibility remains untested--that exposure for a much longer time

to any one or combination of these conditions, especially visual fatigue (such as might be induced by a visual environment within the space craft with an absence of distant objects) might lead to an apparent difficulty in focusing and thus the effective range of accommodation might appear to diminish. However, the various gas mixtures and even the total absence of nitrogen, or partial hypoxia, do not produce a marked change in range of accommodation.

The results of the present experiment clearly show reliable differences among color matches for different targets. With respect to the background matches, the leftmost bands were matched more greenish, the rightmost bands were matched more purplish, and the center bands were matched slightly more blue-greenish. The displacement of the matches from the neutral background matches does not agree in several respects with the matches reported for similar flicker colors by Festinger, Allyn, and White (1971). Perhaps the most obvious inconsistency is that the rightmost bands, which correspond to bands that are usually called blue on Benham's disc are matched with so much green. The differences between the experimental conditions are not significant, however. The various hyperbaric conditions investigated apparently do not affect the color matching of flicker colors or the background. The small differences observed in the group data, e.g. the Condition 1 matches for the left and right bands in Figure 9, are not consistent for different subjects and are best interpreted as experimental variability.

The luminance results are similar to the chromaticity results. There are clear, consistent differences among matches for different targets, but no reliable differences are attributable to the experimental conditions.

CONCLUSIONS

The absence of nitrogen and the change in pressure do not produce any discernable and consistent changes in range of accommodation or color vision, although it was the subjective impression of many of the participants that colors appeared to be different. No tests involving color matching were affected. Thus it would appear that where color vision must be used in space flight, it should be used in such a way that not memory of colors but rather color matches are required. Subjective descriptions of colors might change, but apparently color matches made prior to exposure to space conditions will be the same as those made during space conditions. No decrease in range of accommodation could be documented. Also it did not appear that the retinal circulation was affected in such a way as to disturb any other visual functions.

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Table I. Color Vision Characteristics of Subjects

Subject Number	Age	Sex	H-R-R Plates	Percentile on 100-Hue Test
1	31	M	Normal	50
2	24	M	Normal	65
3	28	M	Normal	80
4	22	F	Normal	90+
5	28	M	Normal	55

Table II. Retinal Vessel Width Measurements. Measurements are in Arbitrary Units to the Same Scale.

Environmental Conditions

Subject	Air at Normal Pressure Arterioles	Air at Normal Pressure Venules	Oxygen at Altitude Arterioles	Oxygen at Altitude Venules
R	6.0	4.5	5.0	4.5
	4.0	9.0	4.0	9.0
	6.0	9.0	6.0	8.5
		5.5		5.5
W	8.0	8.0	7.5	9.0
	5.0	6.0	5.0	7.0
	6.0	9.5	6.0	9.5
Y	4.5	4.0	4.0	3.0
	4.5	3.0	3.5	3.5
	4.0	7.0	3.0	7.5
Total by vessel type	48.0	66.5	44.0	67.0
TOTAL	113.5		111.0	

Table III. Average Change in Range of Accommodation for All Tests and Subjects

Altitude in Feet	Approximate Gas Mixture $\%N_2$ / $\%O_2$	Change at Altitude in Diopters
0 (sea level)	80/20	-0.18
14,000	60/40	-0.06
9,500	80/20	-0.06
7,250	70/30	-0.19
31,500	0/100	-0.42

Table IV. Variation in Range of Accommodation in Diopters for Individual Subjects

Subject	80 N_2/20 O_2 sea level			60 N_2/40 O_2 14,000 ft			80 N_2/20 O_2 9,500 ft			70 N_2/30 O_2 7,250 ft			0 N_2/100 O_2 31,000 ft		
	start	finish	change	start	finish	change	start	finish	change	start	finish	change	start	finish	change
1	4.37	4.37	0.00	4.37	5.12	0.75	3.37	3.49	0.12	3.75	3.75	0.00	3.25	4.49	1.24
	4.24	3.24	-1.00	5.00	4.87	-0.13	3.99	3.37	-0.62	2.99	2.87	-0.12			
2	1.87	1.99	0.12	2.12	3.24	1.12	2.62	1.87	-0.75	2.62	2.74	0.12	3.12	1.99	-1.23
	3.49	3.49	0.00	2.12	2.12	0.00	2.87	2.37	-0.50	2.62	3.12	0.50			
3	5.49	4.99	-0.50	3.87	2.75	-1.12	4.25	3.50	-0.75	3.25	3.25	0.00	3.12	2.50	-1.63
	3.25	3.12	-0.13	3.87	2.75	-1.12	2.50	2.00	-0.50	3.00	2.87	-0.13			
4	5.12	5.12	0.00	4.87	5.12	0.25	4.64	2.62	-2.02	6.12	4.00	-2.12	3.50	2.50	-1.00
	2.75	2.37	-0.38	4.50	3.49	-1.01	2.24	1.87	-0.37	2.87	3.00	0.13			
5	5.12	3.12	0.00	3.37	3.62	0.25	3.50	3.12	-0.38	3.24	2.49	-0.35	3.12	3.62	0.50
	3.49	3.62	0.13	3.62	4.00	0.38	3.24	3.12	-0.12	3.12	3.12	0.00			

Table V. Complete Data for Subject No. 3 (CW) in All Five Conditions

	70 N_2/30 O_2 7250 feet			60 N_2/40 O_2 14,000 feet			0 N_2/ 100 O_2 31,500 feet			80 N_2/ 20 O_2 9,500 feet			80 N_2/ 20 O_2 Sea level		
	x	y	log fL	x	y	log fL	x	y	log fL	x	y	log fL	x	y	log fL
Left Lines	0.368	0.444	0.237	0.383	0.433	0.224	0.309	0.410	0.548	0.407	0.501	0.248	0.355	0.358	0.490
	0.381	0.409	0.210	0.363	0.412	0.221	0.321	0.421	0.548	0.413	0.509	0.248	0.340	0.340	0.184
	0.414	0.471	0.230	0.324	0.361	0.209	0.324	0.415	0.243	0.401	0.544	0.269	0.339	0.391	0.521
	0.390	0.444	0.226	0.308	0.316	0.184	0.333	0.438	0.551	0.416	0.472	0.229	0.335	0.394	0.524
	0.499	0.462	0.188	0.436	0.513	0.241	0.362	0.491	0.263	0.338	0.408	0.231	0.317	0.398	0.236
	0.504	0.457	0.183	0.441	0.480	0.222	0.362	0.500	0.267	0.315	0.372	0.221	0.374	0.458	0.241
	0.416	0.435	0.209	0.419	0.498	0.241	0.382	0.508	0.262	0.328	0.338	0.189	0.328	0.435	0.252
	0.417	0.497	0.241	0.399	0.465	0.233	0.392	0.507	0.257	0.454	0.499	0.226	0.307	0.347	0.208
Mean	0.424	0.452	0.216	0.384	0.435	0.222	0.348	0.461	0.367	0.384	0.455	0.233	0.337	0.390	0.332
Center Lines	0.379	0.562	0.586	0.329	0.499	0.882	0.326	0.474	0.872	0.311	0.441	0.863	0.281	0.447	0.882
	0.311	0.456	0.571	0.306	0.468	0.879	0.313	0.453	0.869	0.343	0.486	0.870	0.311	0.476	0.881
	0.331	0.487	0.576	0.301	0.438	0.867	0.325	0.477	0.874	0.376	0.564	0.587	0.298	0.449	0.875
	0.371	0.547	0.583	0.298	0.442	0.871	0.326	0.497	0.883	0.358	0.513	0.575	0.347	0.539	0.891
	0.347	0.523	0.584	0.299	0.433	0.866	0.347	0.519	0.882	0.304	0.447	0.870	0.306	0.463	0.577
	0.360	0.524	0.578	0.339	0.497	0.877	0.383	0.559	0.583	0.348	0.527	0.885	0.387	0.555	0.879
	0.348	0.524	0.584	0.354	0.529	0.883	0.347	0.521	0.883	0.315	0.461	0.871	0.303	0.430	0.562
	0.376	0.564	0.588	0.331	0.507	0.885	0.334	0.496	0.878	0.341	0.502	0.878	0.379	0.562	0.585
Mean	0.353	0.523	0.581	0.320	0.477	0.876	0.338	0.499	0.841	0.337	0.492	0.800	0.327	0.490	0.766
Right Lines	0.338	0.588	0.313	0.261	0.519	0.324	0.262	0.506	0.319	0.339	0.526	0.289	0.247	0.465	0.309
	0.295	0.597	0.335	0.254	0.500	0.320	0.274	0.507	0.313	0.330	0.551	0.303	0.260	0.548	0.335
	0.295	0.590	0.333	0.308	0.609	0.332	0.271	0.517	0.318	0.274	0.433	0.279	0.304	0.541	0.311
	0.323	0.609	0.326	0.303	0.581	0.326	0.316	0.568	0.315	0.325	0.558	0.308	0.331	0.599	0.319
	0.304	0.573	0.322	0.259	0.495	0.315	0.318	0.594	0.324	0.260	0.501	0.317	0.218	0.436	0.312
	0.301	0.573	0.324	0.285	0.568	0.330	0.288	0.532	0.315	0.265	0.492	0.311	0.320	0.551	0.308
	0.321	0.593	0.322	0.287	0.517	0.310	0.312	0.592	0.326	0.309	0.557	0.315	0.245	0.506	0.327
	0.341	0.593	0.313	0.278	0.533	0.320	0.298	0.559	0.321	0.333	0.577	0.311	0.308	0.525	0.305
Mean	0.315	0.589	0.323	0.280	0.540	0.322	0.292	0.547	0.319	0.305	0.524	0.304	0.279	0.521	0.316
Background	0.396	0.547	0.572	0.392	0.551	0.275	0.396	0.547	0.272	0.394	0.549	0.274	0.386	0.556	0.580
	0.398	0.546	0.271	0.394	0.549	0.274	0.393	0.550	0.275	0.398	0.545	0.271	0.389	0.554	0.578
	0.393	0.550	0.275	0.391	0.552	0.277	0.390	0.535	0.270	0.401	0.543	0.269	0.379	0.562	0.585
	0.402	0.542	0.268	0.395	0.549	0.274	0.382	0.549	0.279	0.396	0.548	0.273	0.389	0.553	0.578
	0.418	0.529	0.255	0.366	0.517	0.273	0.400	0.544	0.269	0.397	0.547	0.272	0.395	0.549	0.274
	0.409	0.537	0.262	0.347	0.480	0.265	0.398	0.546	0.271	0.400	0.545	0.270	0.394	0.550	0.274
	0.398	0.546	0.271	0.355	0.479	0.261	0.391	0.552	0.276	0.345	0.450	0.251	0.385	0.557	0.281
	0.394	0.550	0.274	0.387	0.555	0.280	0.400	0.544	0.269	0.397	0.547	0.272	0.397	0.547	0.272
Mean	0.401	0.543	0.306	0.378	0.529	0.272	0.394	0.546	0.273	0.391	0.534	0.269	0.389	0.553	0.428

Figure 1

Head tent and associated equipment. A sample tube (not shown) is connected to the head tent. The O_2 flow is adjusted to maintain the proper gas mixture constant.

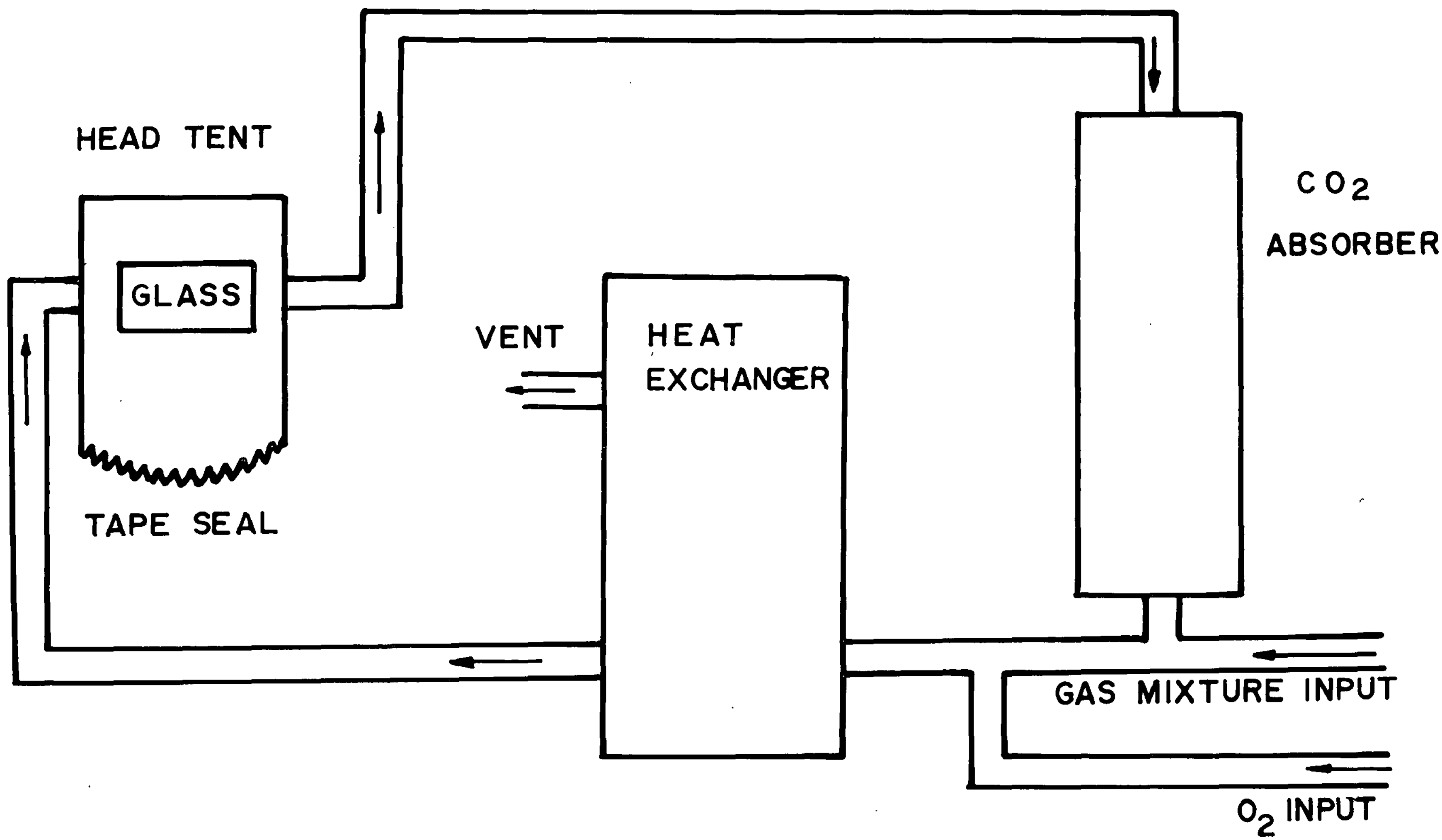

HEAD TENT
GLASS
TAPE SEAL
VENT
HEAT
EXCHANGER
CO_2
ABSORBER
GAS MIXTURE INPUT
O_2 INPUT

FIG. 1

Figure 2

Target for accommodation test. The laser spot with the speckle pattern is displaced from the point of fixation--the central line crossing--as shown. The target is shown approximately full size and was made of silk thread (#5-0) stretched on a frame.

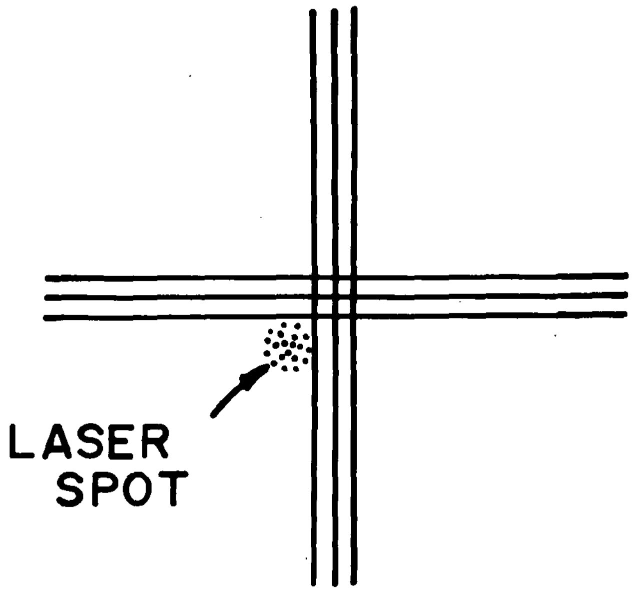


FIG. 2

Figure 3

Appearance of the stimulus field. The cross-hatched area on the left is the colorimeter field. The remaining rectangular area is the flicker-color field. The surround is dark. The subject adjusted the color of the colorimeter field to match either the left set of three vertical bands, the center bands, the right bands, or the background area between the sets of bands.

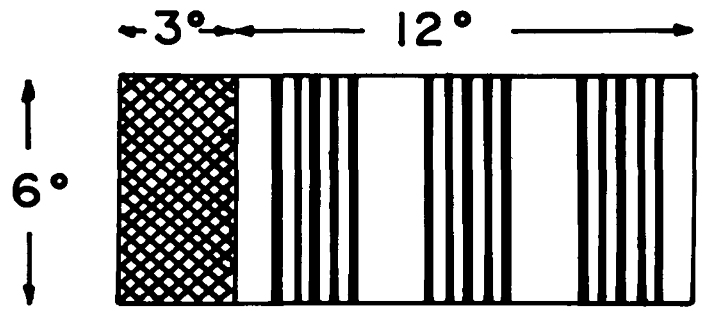


FIG. 3

Figure 4

Schematic top view of the flicker-color matching apparatus. See text for description.

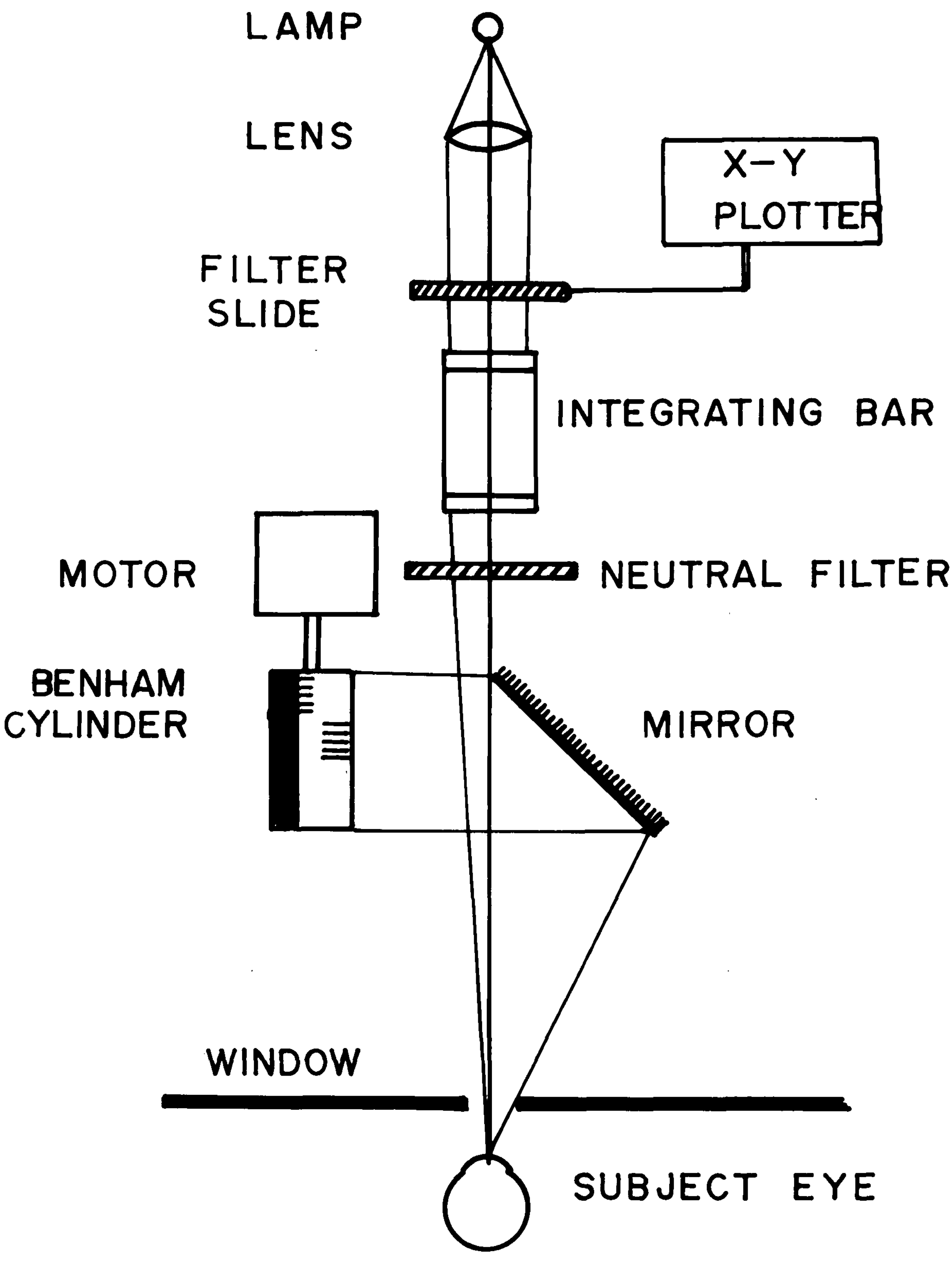

LAMP
LENS
X-Y
PLOTTER
FILTER
SLIDE
INTEGRATING BAR
MOTOR
NEUTRAL FILTER
BENHAM
CYLINDER
MIRROR
WINDOW
SUBJECT EYE

FIG. 4

Figure 5

The flicker-color stimulus pattern that covered the rotating cylinder. The cylinder is half-black and half-white, with three sets of 60 degree line segments on the white half.

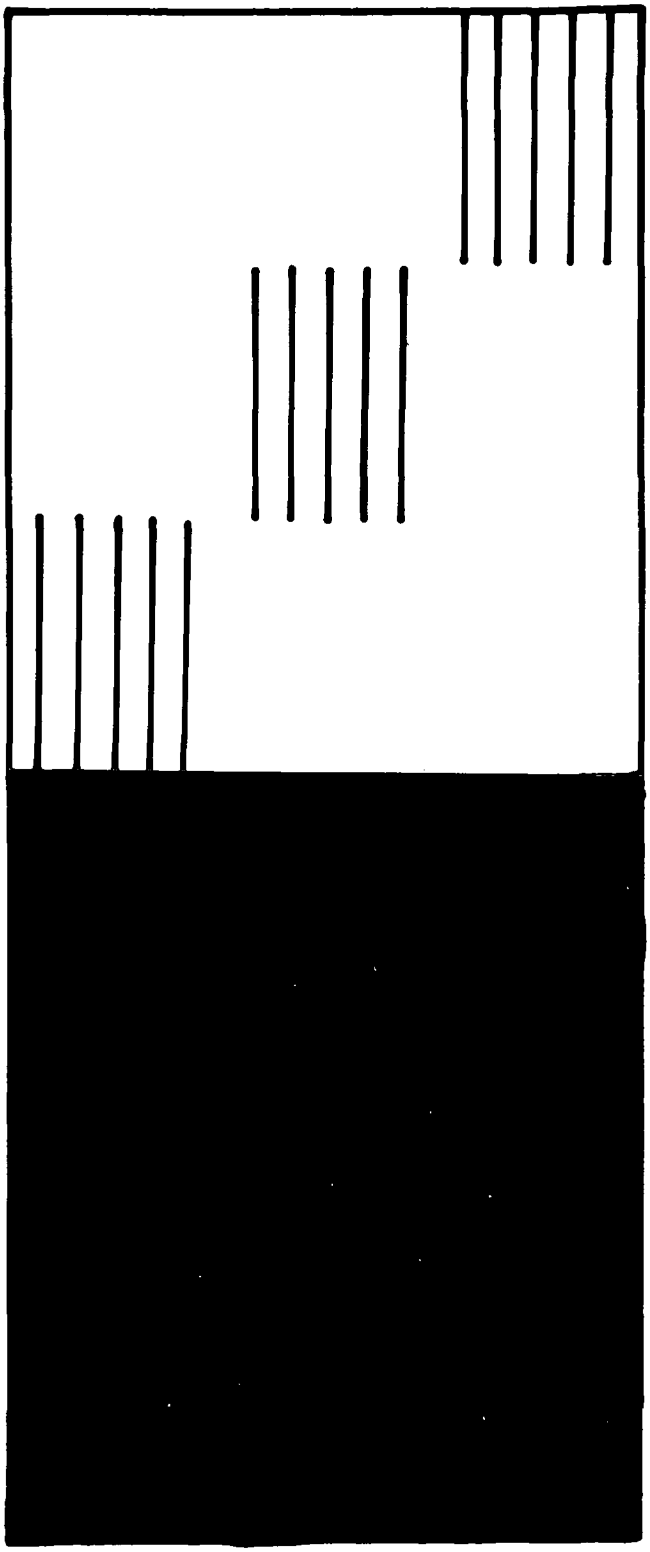


FIG. 5

Figure 6

Typical photograph of the retinal vessels in red-free light. The positions selected for measurement on the negative are indicated by letters.

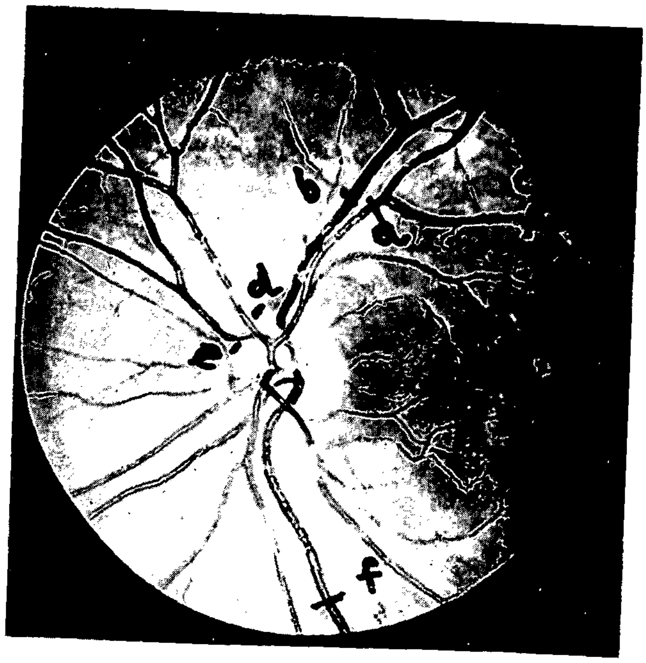
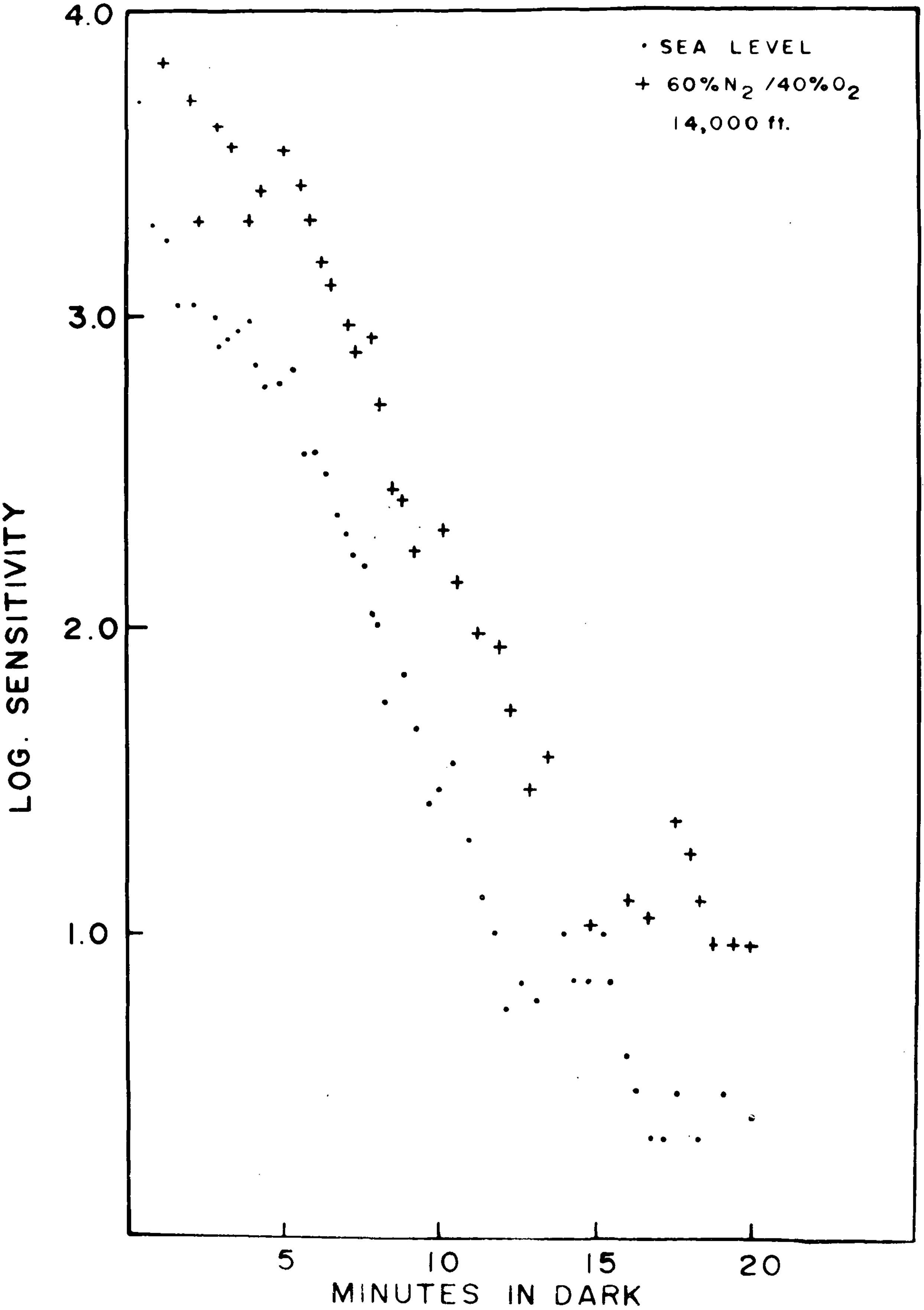


FIG. 6

Figure 7

Dark adaptation curves at sea level and after breathing 60% N_2/ 40% O_2 at 14,000 feet. The curve taken at altitude has been displaced upward 0.3 log unit in sensitivity to allow comparison.

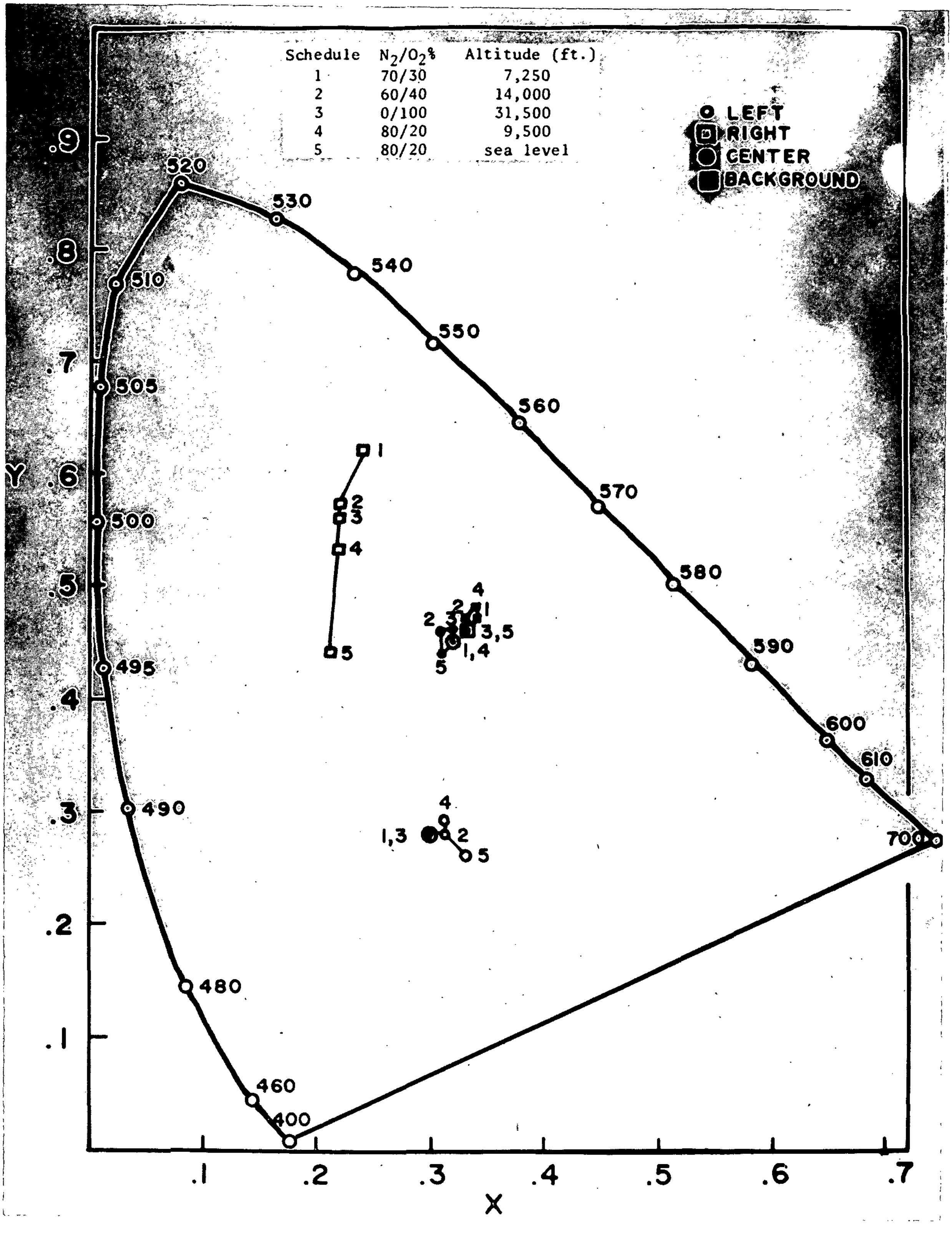


4.0
3.0
2.0
1.0
LOG. SENSITIVITY
· SEA LEVEL
+ 60% N_2 /40% O_2
14,000 ft.
5
10
15
20
MINUTES IN DARK

FIG. 7

Figure 8

Mean color matches in all experimental conditions plotted as 1931 CIE x,y chromaticity coordinates. These results are the means for all five subjects.

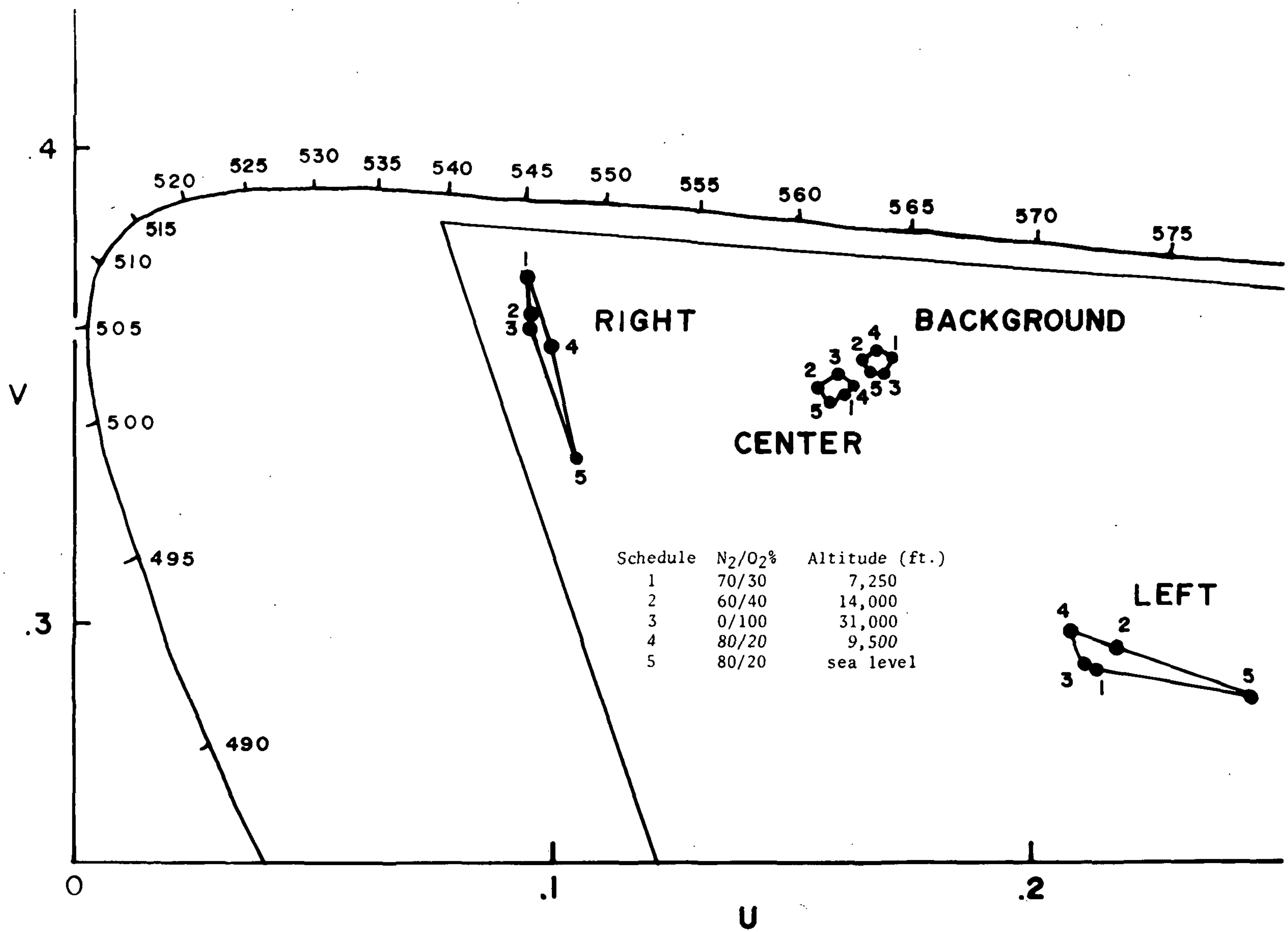


Schedule N2/O2% Altitude (ft.)
1 70/30 7,250
2 60/40 14,000
3 0/100 31,500
4 80/20 9,500
5 80/20 sea level
LEFT
RIGHT
CENTER
BACKGROUND
Y
X

FIG. 8

Figure 9

Mean color matches in all experimental conditions plotted on the CIE 1960 u,v uniform chromaticity space diagram. These results are the means for all five subjects.

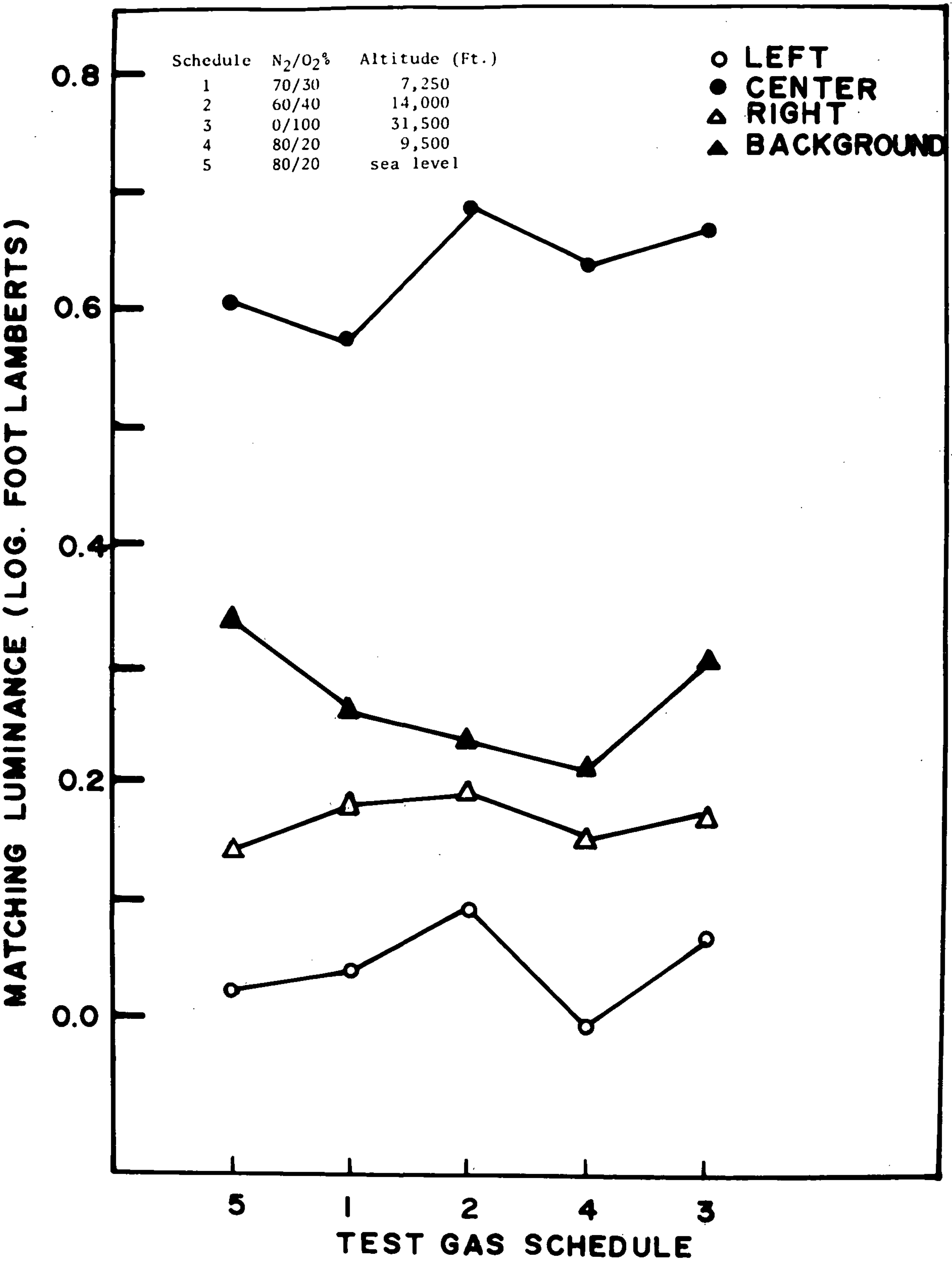


V
U
.4
.3
0
.1
.2
520
525
530
535
540
545
550
555
560
565
570
575
515
510
505
500
495
490
RIGHT
BACKGROUND
CENTER
LEFT
Schedule N$_2$/O$_2$% Altitude (ft.)
1 70/30 7,250
2 60/40 14,000
3 0/100 31,000
4 80/20 9,500
5 80/20 sea level

FIG. 9

Figure 10

Luminances of colorimeter matches for the four targets in five experimental conditions. These results are the means for all five subjects.



Schedule N2/O2% Altitude (Ft.)
1 70/30 7,250
2 60/40 14,000
3 0/100 31,500
4 80/20 9,500
5 80/20 sea level
LEFT
CENTER
RIGHT
BACKGROUND
MATCHING LUMINANCE (LOG. FOOT LAMBERTS)
0.8
0.6
0.4
0.2
0.0
5
1
2
4
3
TEST GAS SCHEDULE

FIG. 10

Figure 11

Electroretinograms (ERG) showing comparison between dark and light adapted states at sea level and 100% O_2 at 31,000 feet. In each pair the left eye is on top. The numbers indicate the order in which the records were taken. Records 1, 2, and 3 are to the same voltage scale, record 4 has twice the gain of the others.

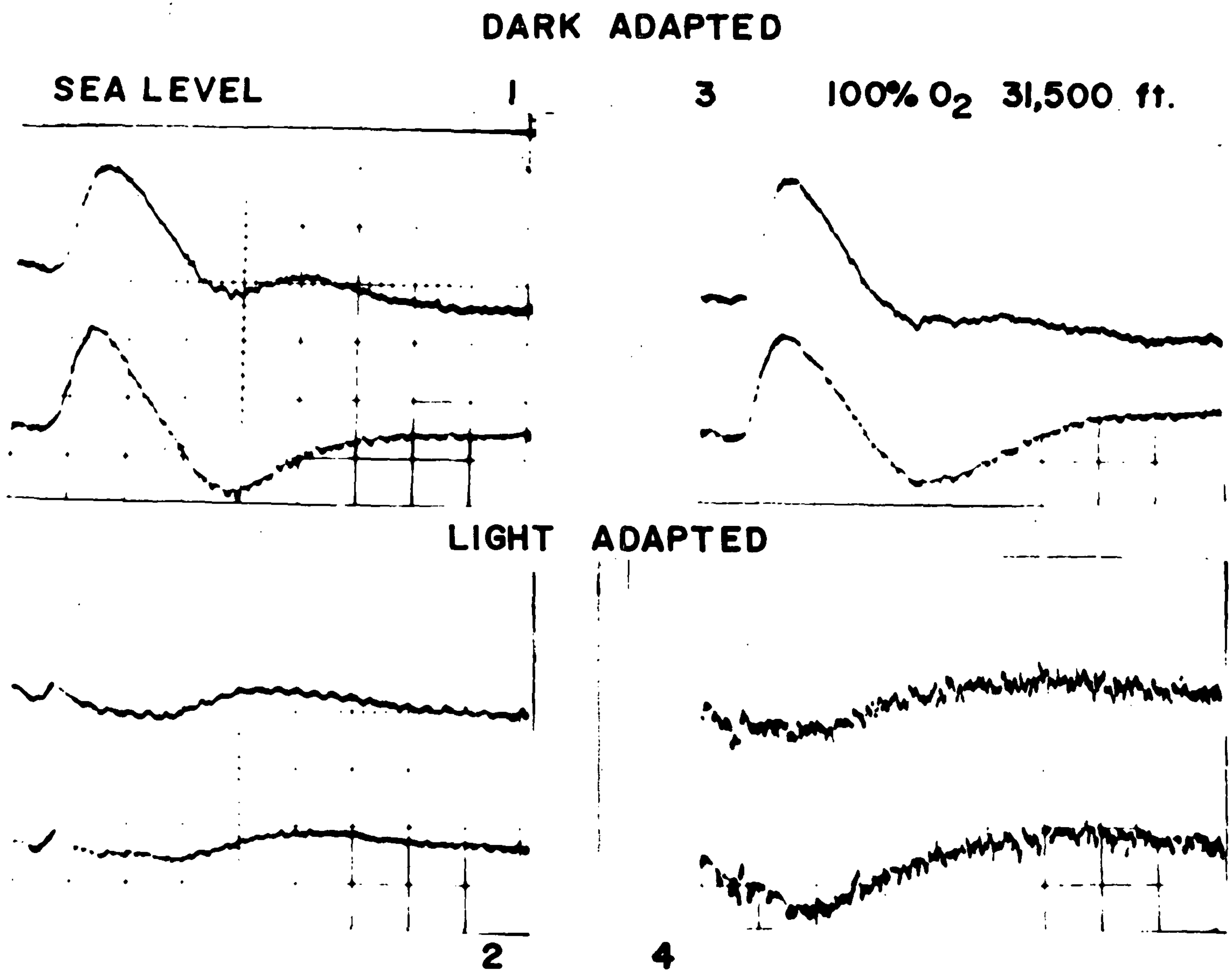


FIG. 11